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PALEOMAGNETISM OF COASTAL CALIFORNIA AND BAJA CALIFORNIA: ALTERNATIVES TO LARGE-SCALE NORTHWARD TRANSPORT

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Abstract. Paleomagnetic data from the Santa Lucia-Orocopia (SLOA) and Baja-Borderland (BBA) allochthons of coastal California and Baja California have been interpreted to indicate up to 2500 km of post-mid-Cretaceous northward transport of these regions with respect to interior North America. However, with Neogene strike-slip offsets taken into account, geological interpretations correlate basement rocks of the coastal allochthons with continental basement rocks directly across the San Andreas and related fault systems. We have examined paleomagnetic data from SLOA and BBA and conclude that apparent discordances can be explained without large-scale pre-Neogene tectonic transport. Three major observations are fundamental to this analysis: (1) Paleolatitudes derived from volcanic rocks of the Jurassic Eugenia Formation of BBA and Coast Range ophiolite of SLOA are concordant when compared to revised Jurassic reference paleomagnetic poles from interior North America. (2) Isotopic and paleobarometric data from the Peninsula Ranges batholith in southern California indicate that the batholith has been tilted northeast-side-up by an amount that can account for discordant paleomagnetic directions observed in plutonic rocks of the batholith without large-scale northward transport. (3) Literal interpretation of the paleolatitudes determined from paleomagnetic directions in Upper Cretaceous and Paleogene marine sedimentary rocks of SLOA and BBA requires north-then-south-then-north transport and a complex motion history between the two allochthons. However, concordant paleolatitudes are indicated by some sedimentary rocks while coeval or younger sedimentary rocks of the same allochthon have discordant paleolatitudes. Coupled with recent documentations of compaction shallowing of paleomagnetic inclination in other marine sedimentary rocks, these inconsistencies suggest that paleolatitudes derived from most of the marine sedimentary rocks of SLOA and BBA are biased towards low paleolatitudes by compaction shallowing.

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1. INTRODUCTION

Paleomagnetic data from western California and Baja California have been interpreted to indicate large-scale (1000-2500 km) northward transport with respect to interior North America during late Mesozoic and early Cenozoic time [Champion et al., 1984; Hagstrum et al., 1985; Morris et al., 1986; Howell et al., 1987]. The data have been obtained from a variety of Mesozoic and Cenozoic rocks, and the pattern of discordant paleomagnetic directions shows a significant degree of apparent internal consistency. But the large-scale northward transport interpreted from discordant paleomagnetic directions is countered by a number of geological arguments. As the conflict between extant geological and paleomagnetic interpretations poses a well-known paradox, we briefly cite key references presenting the geological viewpoint and then focus attention here on alternate interpretations of the paleomagnetic data.

Geological interpretations suggest that basement rocks of the Salinian block can be matched with counterparts in the Tehachapi Mountains of the Sierra Nevada block when allowance is made for Neogene slip along the San Andreas fault [Ross, 1985; James and Mattinson, 1988]. This cross-fault correlation is significant because all workers agree that the Sierra Nevada batholith has experienced only minor movement with respect to the continental interior since mid-Mesozoic time [Frei, 1986]. Inferred basement correlations across the San Andreas fault between the Tujunga terrane of the Transverse Ranges and the nearby Mojave block also relate the coastal allochthons directly to the adjacent continent [May and Walker, 1989]. Moreover, the nature of Paleozoic and Mesozoic rocks in Baja California is compatible with a position of peninsular California adjacent to nearby mainland Mexico prior to Cenozoic opening of the Gulf of California [Gastil and Miller, 1984].

We have evaluated paleomagnetic data from regions referred to as the Santa Lucia-Orocopia (SLOA) and Baja-Borderland (BBA) allochthons (named by Vedder et al. [1982] and Champion et al. [1986]; the latter is similar to the Peninsular Ranges terrane (PRT) of Morris et al. [1986]). Our intent is to examine whether alternate interpretations that do not involve significant tectonic transport can explain the paleomagnetic observations. We argue that three important factors have led to the incorrect impression that paleomagnetic data from SLOA and BBA require large-scale northward transport:

1. Isotopic and paleobarometric data from the Peninsula Ranges batholith in southern California indicate that tilting of these plutonic rocks about an axis subparallel to the trend of the batholith can largely account for the observed discordant paleomagnetic directions without large-scale northward transport.
2. Revisions to the Mesozoic apparent polar wander (APW) path for North America affect interpretations of paleomagnetism in Triassic and Jurassic rocks. Based on earlier versions of the Mesozoic APW path, previous interpretations of paleomagnetic data from Jurassic volcanic rocks of SLOA significantly overestimated northward transport.
3. Inconsistencies of paleomagnetically determined paleolatitudes between various types of sedimentary rocks of SLOA and BBA suggest that paleolatitudes derived from most of the marine sedimentary rocks are biased towards low paleolatitudes by compaction shallowing of paleomagnetic inclination.

We freely admit to a philosophy of attempting to explain the paleomagnetic observations within what some will regard as a "minimum motion" geological framework as a means to resolve the dichotomy between current paleomagnetic and strictly geologic interpretations. The degree to which our approach and conclusions have been affected by this philosophy can be judged only by the reader. Many of our conclusions are well supported by geologic data from SLOA and BBA. However, other conclusions are more speculative because the arguments and observations are less direct. Having stated these caveats, we offer our interpretations as a potentially testable counterpoint to previous interpretations favoring large-scale northward transport.

We first present a summary of previous paleomagnetic observations and interpretations. In our view, the historical context is significant for understanding the basis of these interpretations. A palinspastic reconstruction of western and Baja California is then used to provide a paleogeographic framework within which to compile paleomagnetic observations. We then present evidence for tilting of plutonic rocks as the primary explanation for discordant paleomagnetic directions from the Peninsular Ranges batholith. Our compilation and analysis of paleomagnetic data from SLOA and BBA then leads to separate discussions of results from Jurassic volcanic rocks and Cretaceous-Paleogene sedimentary rocks. In our judgment, all discordant paleomagnetic inclinations are best explained by tilting of granitic plutons about subhorizontal axes or by compaction shallowing of paleomagnetic inclinations in marine sedimentary rocks.

2. PALEOMAGNETIC EVIDENCE FOR LARGE-SCALE NORTHWARD TRANSPORT: INTERNAL CONSISTENCY OR SYSTEMATIC BIAS?

The initial observation of discordant paleomagnetic directions from southern California was made by Teissere and Beck [1973] from the Peninsular Ranges batholith. Implicitly assuming that present horizontal equals paleohorizontal, Teissere and Beck [1973] interpreted the 11.5° shallowing of paleomagnetic inclination as evidence for northward transport. The clockwise deflection of the observed declination from the expected declination was interpreted to indicate clockwise vertical axis rotation. By comparisons with paleomagnetic directions of the associated Siletz River volcanics and Yachats basalts, Simpson and Cox [1977] showed that the paleomagnetism of Eocene turbidites in the Oregon Coast Range (Tyee and Flournoy formations) accurately record the Eocene geomagnetic field direction. This observation encouraged others to undertake paleomagnetic studies of various marine sedimentary rocks of SLOA and BBA. As discussed below, recent studies indicate that many (if not most) marine sediments suffer compaction shallowing of paleomagnetic inclination; the Tyee and Flournoy formations may be the exception rather than the rule.

Paleomagnetic data from Jurassic volcanic rocks of the Coast Range ophiolite and Upper Cretaceous turbidites of the Stanley Mountain terrane were reported by McWilliams and Howell [1982]. Using a paleomagnetic reference pole from the compilation of Irving [1979], the paleomagnetic direction from the Jurassic volcanic rocks was interpreted to indicate ~15° of northward latitudinal transport. The highly discordant paleomagnetic direction from the turbidites was interpreted to indicate ~40° of latitudinal transport. As discussed below, the paleomagnetic data from the Coast Range ophiolite are the only available data from Mesozoic volcanic rocks of SLOA.

Results of an extensive paleomagnetic study of Cretaceous and Paleocene turbidites of the Salinia terrane were presented by Champion et al. [1984]. The pattern of discordant paleomagnetic inclinations was interpreted to indicate ~2500 km of northward transport of Salinia between Late Cretaceous and Eocene time. Kanter and Debiche [1985] and Kanter [1988] subsequently confirmed the necessity for arrival of Salinia by Eocene time, at the latest, through observations of concordant paleolatitudes from the Eocene Butano Sandstone. With the paleomagnetic data then available the progressive northward motion model for Salinia advanced by Champion et al. [1984] was internally consistent and appealingly simple.

Paleomagnetic data from the Upper Cretaceous Valle Formation of Baja California showed shallow inclinations and were interpreted to indicate subsequent northward transport of the peninsula by >1000 km [Patterson, 1984]. A major paleomagnetic investigation of Mesozoic units from Baja California was reported by Hagstrum et al. [1985]. The greatly expanded paleomagnetic data base from the Peninsular Ranges batholith and from Cretaceous sedimentary rocks confirmed the discordant paleomagnetic directions observed by Teissere and Beck [1973] and by Patterson [1984]. Hagstrum et al. [1985] did consider the possibility of inclination errors in the sedimentary rocks and unrecognized tilting of plutonic rocks but discounted these explanations because of consistency of paleomagnetic results from sedimentary and plutonic rocks over a wide area. They concluded that the discordant paleomagnetic directions indicated ~11° of post-Cretaceous (but pre-15 Ma) northward latitudinal transport of Baja California relative to interior North America.

Hagstrum et al. [1985] also reported limited paleomagnetic data from Jurassic volcanic rocks of the Eugenia Formation which are still the only paleomagnetic data from pre-Miocene volcanic rocks of BBA. In addition, Hagstrum et al. [1985] discussed the observation that then-available paleomagnetic poles from Cretaceous rocks of BBA clustered about the present geographic pole and no reversed polarity magnetizations were observed. Because the ages of many of these rocks fall within the Cretaceous normal polarity superchron, primary magnetizations are expected to be entirely normal polarity. Thus the reversals test of paleomagnetic stability cannot be applied. But the observation of paleomagnetic poles clustering about the present geographic pole raises the specter that the observed paleomagnetic directions result from recent remagnetization. Based partly on their thorough laboratory examinations of paleomagnetic stability, Hagstrum et al. [1985] concluded that this clustering of paleomagnetic poles from BBA about the geographic pole is coincidental. This conclusion has since been confirmed by paleomagnetic data from Upper Cretaceous and Paleogene rocks of BBA which provide reversals tests and fold tests of paleomagnetic stability [Fry et al., 1985; Morris et al., 1986; Filmer and Kirschvink, 1989].

Morris et al. [1986] and Champion et al. [1986] made the intriguing observation that paleomagnetically determined paleolatitudes from rocks of PRT ≈ BBA ranging in age from Jurassic to Miocene are systematically lower than for adjacent portions of North America by about the same amount. Morris et al. [1986, p. 846] interpreted this consistent paleolatitudinal difference to indicate that PRT had "drifted as part of North America for most of its geologic history but that during this time [>15 Ma] it was located about 15° lower in latitude relative to the stable craton." They inferred that ~15° of northward motion had occurred within the interval 5-15 Ma. In agreement with the observations of Morris et al. [1986], paleomagnetic data from Cretaceous and Eocene marine sediments of the San Nicolas terrane also yielded paleolatitudes implying ~15° of latitudinal displacement [Champion et al., 1986]. However, contrary to the timing of northward transport suggested by Morris et al. [1986], Hagstrum et al. [1987] presented an analysis of paleomagnetic data from Miocene volcanic rocks of Baja California arguing that Baja California was in its pre-Gulf of California position no later than early Miocene time. Howell et al. [1987] presented a summary of the paleolatitudinal motion histories interpreted from paleomagnetic data and arguments for allochthoneity of SLOA and BBA.

Discordant paleomagnetic directions from the Upper Cretaceous Point Loma Formation at San Diego have recently been interpreted by Bannon et al. [1989] to indicate ~20° of northward displacement coupled with ~50° of clockwise vertical axis rotation. Filmer and Kirschvink [1989] also recently presented a detailed analysis of the paleomagnetism of the Upper Cretaceous Rosario Formation nearby in Baja California. They interpreted these data to indicate northward latitudinal transport by ~15° with ~30° of clockwise vertical axis rotation. Filmer and Kirschvink [1989, p. 7340-7341] stated that: "Magnetic inclination shallowing during sediment compaction has been ruled out by collection of data from sedimentary and plutonic rocks on the peninsula which show similar results as well as the consistency from site to site within all data sets."

However, Flynn et al. [1989] recently reported concordant paleomagnetic inclinations from intertonguing marine (Bateque Formation) and continental (Las Tetas de Cabra Formation) sediments of early Eocene age in Baja California which challenge the apparent internal consistency of the paleomagnetic observations. In sharp contrast to the indications of ~15° of post-Eocene latitudinal transport of the San Nicolas terrane of BBA, Flynn et al. [1989, p. 1194] concluded that there has been "no significant post-early Eocene northward translation of Baja California." Recognizing the conflict with previous interpretations of paleomagnetic data from BBA, Flynn et al. [1989] speculated that the discrepancies between paleomagnetic studies in various regions of BBA may be due to independent motion of smaller terranes that previously had been considered parts of large composite terranes.

An important internal inconsistency has also become evident in the Paleogene paleolatitudes of SLOA inferred from paleomagnetism of sedimentary rocks. Paleomagnetic inclinations from the Eocene Butano Sandstone indicate concordant paleolatitudes when Neogene offset by the San Andreas fault is taken into account [Kanter, 1988]. However, Liddicoat [1990] has reported paleomagnetic data from the Oligocene Sespe Formation of SLOA in the Santa Ynez Range which are inferred to indicate ~10° of post-Oligocene northward transport.

We argue below that the apparent internal consistency of paleomagnetic results from plutonic and sedimentary rocks of BBA is the result of near coincidence of two effects: (1) consistent northeast-side-up tilting of the Peninsular Ranges batholith to produce the observed discordant paleomagnetic directions from the batholith, and (2) compaction shallowing of paleomagnetic inclinations in the marine sedimentary rocks. Without strong geological evidence for tilting of the Peninsular Ranges batholith and at least indirect evidence for compaction shallowing in the sedimentary rocks, this suggested explanation for the paleomagnetic observations from SLOA and BBA would be pure speculation. However, abundant petrologic and isotopic evidence for tilting of the Peninsular Ranges batholith does exist. And important inconsistencies in latitudinal motion histories interpreted from paleomagnetism of sedimentary rocks of SLOA and BBA seemingly reflect the influence of compaction shallowing.

Southerly paleolatitudes determined from limestones of the Franciscan assemblage in the California Coast Ranges [Alvarez et al., 1980; Courtillot et al., 1985; Tarduno et al., 1985, 1986, 1990] are not treated here. These rocks are accepted as components of an accretionary wedge developed along the continental margin. Their paleolatitudes reflect the former location of the oceanic substratum from which they were detached during subduction. These paleolatitudes do not pertain directly to basement rocks now present along the continental margin. Remagnetization of deformed Franciscan rocks may reflect events related to their accretion along the continental margin [Hagstrum and Sedlock, 1990; Hagstrum, 1990], but remagnetization raises challenging questions of interpretation that are beyond the scope of this paper.

3. TECTONIC RESTORATIONS

Evaluation of available data from Mesozoic and Paleogene paleomagnetic localities in coastal California and Baja California requires varied palinspastic restorations to reverse the effects of Neogene deformation along the San Andreas fault system and related structures. As valid comparisons must be based on the same set of assumptions applied consistently to all paleomagnetic sites, we have performed an independent tectonic reconstruction rather than relying upon expected paleolatitudes cited by different authors for different sites. Reconstructed positions of paleomagnetic sites (Table 1) were determined from present geographic positions (Figure 1) by the following combined tectonic restorations of Neogene fault slip and block rotation (Figure 2):

1. Reversal of 110 km of dextral slip on the San Gregorio-Hosgri fault [Dickinson, 1983] to pull a coastal sliver of crust down along the flank of the Salinian block (affects only German Rancho Formation near Gualala and Pigeon Point Formation near Half Moon Bay).
2. Reversal of 60 km of sinistral slip on the Garlock fault [Davis and Burchfiel, 1973] and 16 km of sinistral slip on the

TABLE 1. Paleomagnetic Data From the Santa Lucia-Orocopia and Baja-Borderland Allochthons

Unit	Terrane (map location)	Age, Ma	Recon. Location		Paleolatitude, °N	Pole	Paleolatitude', °N	N. Transport deg	Rotation, deg	Reference
			Lat °N	Long °E						
Sespe Fm	Sur-Obispo (21)	32±5	30.7	244.5	22.0± 3.9	Ol	31.9 ± 4.0	9.9 ± 4.4	80.1± 6.9	M
Poso-Canada and South Point fms	San Nicolas (7)	48±6	30.4	243.6	17.3± 2.4	Eo	32.2 ± 3.0	14.9 ± 3.1	~70	A
Butano Sandstone	Salinia (3)	52±2	35.7	240.7	34.6± 4.9	Eo	37.8 ± 3.0	3.2 ± 4.6		B
German Rancho Fm	Salinia (1)	55±7	36.2	240.2	25.0± 1.4	Eo	38.4 ± 3.0	13.4 ± 2.6		C
Las Tetas de Cabra Fm	Santa Ana (15)	55±1	26.6	248.7	31.1± 3.6	Eo	27.8 ± 3.0	-3.2 ± 3.8	-5.1± 3.6	D
Bateque Fm	Santa Ana (15)	55±1	26.6	248.7	23.3± 5.7	Eo	27.8 ± 3.0	4.6 ± 5.2	-18.7± 5.5	D
Silverado Fm	Santa Ana (9)	60±2	31.6	245.3	25.2± 6.9	Pal	36.5 ± 3.2	11.3 ± 6.1	-17.6± 8.2	E
Point San Pedro Fm	Salinia (2)	60±4	35.9	240.6	24.5± 4.0	Pal	41.3 ± 3.2	16.8 ± 4.1	60 to 160	F
Punta Baja Fm	Santa Ana (13)	70±3	27.7	247.0	28.8±10.5	Cret	38.4 ± 4.9	9.6 ± 11.2	21.4±11.8	G
Pigeon Point Fm	Salinia (4)	72±6	34.7	241.2	21.2± 5.3	Cret	46.6 ± 4.9	25.4 ± 5.8	-20 to 30	F
Point Loma Fm; N	Santa Ana (11)	72±2	30.4	245.7	22.4± 3.9	Cret	41.3 ± 4.9	18.9 ± 5.0	47.3± 6.2	H
Point Loma Fm; R	Santa Ana (11)	72±2	30.4	245.7	20.2±11.7	Cret	41.3 ± 4.9	21.1 ± 10.1	54.2±14.0	H
Punta Baja and Rosario fms	Santa Ana (13)	74±6	27.7	247.0	26.2± 6.6	Cret	38.4 ± 4.9	12.2 ± 6.5	22.3± 8.5	E
Rosario Fm (Punta San Jose)	Santa Ana (12)	77±3	29.2	246.3	25.2± 1.9	Cret	40.0 ± 4.9	14.8 ± 4.4	22.9± 4.8	G
Tuna Canyon Fm	Malibu (8)	80±10	31.6	244.9	28.1± 5.4	Cret	42.7 ± 4.9	14.6 ± 5.8	92.5± 7.4	E
Ladd and Williams fms	Santa Ana (9)	82±8	31.6	245.3	26.6± 5.4	Cret	42.6 ± 4.9	15.9 ± 5.8	-16.8± 7.5	E
Jalama Fm	San Nicolas (7)	87±3	30.4	243.6	25.7± 2.0	Cret	41.9 ± 4.9	16.2 ± 4.2	50.0± 5.7	A
Valle Fm (Malarrimo)	Vizcaino (18)	85±1	25.7	248.4	22.5± 8.5	Cret	36.1 ± 4.9	13.6 ± 7.8	25.4±13.1	I
Valle Fm (Malarrimo)	Vizcaino (18)	87±1	25.7	248.4	20.0± 5.2	Cret	36.1 ± 4.9	16.1 ± 5.7	33.7± 9.0	I
Valle Fm (Malarrimo)	Vizcaino (18)	90±2	25.7	248.4	25.1± 4.1	Cret	36.1 ± 4.9	11.0 ± 5.1	32.1± 7.6	I
Fish Creek turbidites	Stanley Mtn (6)	90±4	33.0	243.9	6.1± 5.7	Cret	44.3 ± 4.9	38.2 ± 6.0	42.8± 8.5	K
Valle Fm (Cedros Island)	Vizcaino (16)	90±2	26.1	247.8	22.1± 4.9	Cret	36.6 ± 4.9	14.5 ± 5.6	6.1± 7.0	I
Valle Fm (San Lorenzo)	Vizcaino (19)	90±2	24.9	249.3	25.4± 2.2	Cret	35.1 ± 4.9	9.7 ± 4.3	10.9± 5.4	I
Valle Fm (El Plallon)	Vizcaino (18)	90±2	25.7	248.1	32.0± 6.0	Cret	36.2 ± 4.9	4.2 ± 6.2	-21.6± 9.7	I
Valle Fm (La Pitahaya)	Vizcaino (19)	94±2	24.9	249.3	20.3± 1.4	Cret	35.1 ± 4.9	14.8 ± 4.1	14.2± 5.3	I
Valle Fm	Vizcaino (18)	94±8	25.8	248.1	23.9±12.1	Cret	36.3 ± 4.9	12.4 ± 10.4	28.4± 9.2	J
Eugenia Fm	Vizcaino (17)	150±5	25.7	248.1	13.5± 8.6	P150	18.7 ± 5.0	5.2 ± 8.0	19.8±18.9	J
Eugenia Fm	Vizcaino (17)	150±5	25.7	248.1	13.5± 8.6	Glance	11.6 ± 6.3	-1.9 ± 8.5	22.3±19.2	J
Coast Range ophiolite	Stanley Mtn (5)	160±5	33.2	243.8	14.3± 4.8	Corral	13.9 ± 6.2	-0.4 ± 6.3	-116.4± 8.8	K
Coast Range ophiolite	Stanley Mtn (5)	160±5	33.2	243.8	14.3± 4.8	P160	20.7 ± 5.0	6.4 ± 5.5	-117.2± 8.4	K
Coast Range ophiolite	Stanley Mtn (5)	160±5	33.2	243.8	14.3± 4.8	Glance	19.9 ± 6.3	5.6 ± 6.3	-112.2± 8.9	K
Peninsular Ranges batholith										
southern California	Santa Ana (10)	110±5	31.0	246.0	29.6± 2.6	Cret	41.8 ± 4.9	12.1 ± 4.4	25.4± 5.3	J,L
San Ignacito	Cortes (14)	95±5	27.5	248.3	34.5± 3.5	Cret	37.8 ± 4.9	3.3 ± 4.8	24.4± 5.6	J
San Bartolo	La Paz (20)	105±10	21.9	253.1	32.1±13.0	Cret	31.1 ± 4.9	-0.9 ± 11.1	25.9±14.8	J

Unit: geological formation (Fm), formations (fms) or rock unit; N, normal-polarity sites only; R, reversed-polarity sites only; name in parentheses indicates the particular location within a formation. Terrane: tectonostratigraphic terrane designation of Silberling et al. [1978] and Coney and Campa [1987]; map location number is identification number on Figure 1; age given is estimated mean age with probable age range indicated by ± number. Recon. location: site location reconstructed relative to interior North America (see text); Lat, latitude; Long, longitude; reconstructed location for Eugenia Formation is mean of Punta Eugenia and Puerto Escondido sites. Paleolatitude: observed paleolatitude (and 95% confidence limits) determined from the observed paleomagnetic direction. Pole: paleomagnetic reference pole (see listing below). Paleolatitude: expected paleolatitude (and 95% confidence limits) determined from the paleomagnetic reference pole. N. Transport: apparent northward transport (and 95% confidence limits) indicated by the difference between the expected and observed paleolatitudes. Rotation: vertical axis rotation implied by difference between observed and expected declination, positive value indicates clockwise rotation, negative value indicates counterclockwise rotation. References: A, Champion et al. [1986]; B, Kanter [1988]; C, Kanter and Debiche [1985]; D, Flynn et al. [1989]; E, Morris et al. [1986]; F, Champion et al. [1984]; G, Filmer and Kirschvink [1989]; H, Bannon et al. [1989]; I, Patterson [1984]; J, Hagstrum et al. [1985]; K, McWilliams and Howell [1982] and J. G. Vedder (personal communication, 1990); L, Teissere and Beck [1973]; M, Liddicoat [1990]. Paleomagnetic reference poles: Ol, Oligocene (84.0°N, 168.0°E, A_{95} = 4.0°) [Diehl et al., 1988]; Eo, Eocene (82.8°N, 170.4°E, A_{95} = 3.0°) [Deihl et al., 1983]; Pal, Paleocene (81.5°N, 192.6°E, A_{95} = 3.2°) [Diehl et al., 1983]; Cret, Cretaceous (71.0°N, 196.0°E, A_{95} = 4.9°) [Globerman and Irving, 1988]; P150, PEP 150 Ma pole (68.3°N, 143.9°E, A_{95} = 5.0°) [Gordon et al., 1984]; Glance, 151 Ma Glance Conglomerate (formerly Canelo Hills) pole (62.7°N, 131.5°E, A_{95} = 6.3°) [Kluth et al., 1982]; Corral, 172 Ma Corral Canyon pole (61.8°N, 116.0°E, A_{95} = 6.2°) [May et al., 1986]; P160, PEP 160 Ma pole (67.0°N. 126.5°E, A_{95} = 5.0°) [Gordon et al., 1984].

Pinto Mountain fault [Crowell and Ramirez, 1979] to straighten the course of the San Andreas fault through the Transverse Ranges (allowing the Mojave block to distort internally to align San Andreas traces within central California and beside the Salton Sea).

3. Reversal of 320 km of dextral slip on the San Andreas fault [Stanley, 1987; Graham et al., 1989] north of the Transverse Ranges (and on branching San Andreas and San Gabriel faults through the Transverse Ranges), with comparable extension restored on linked spreading centers joined by transforms in the Salton Trough and the Gulf of California.

4. Counterclockwise rotation of the east-west Santa Ynez Range and Santa Monica Mountains by 75° about a pivot point at the east end of the western Transverse Ranges [Hornafius et al., 1986].

5. North of the Transverse Ranges, reversal of 45 km of

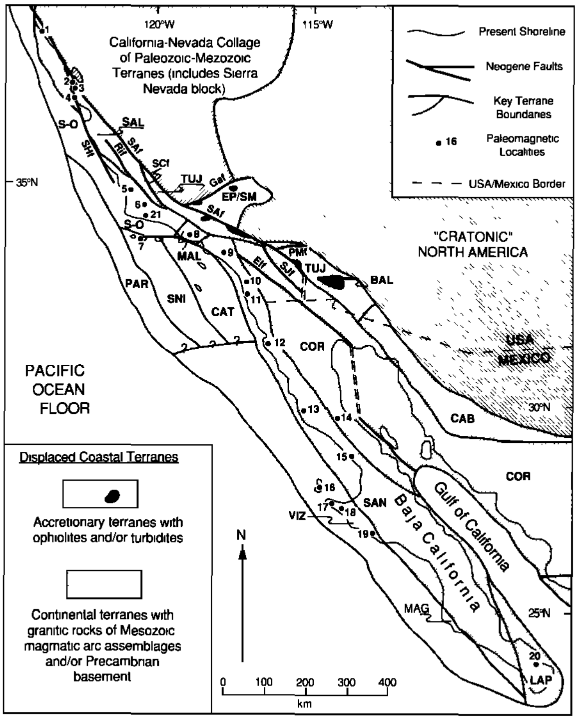

Figure 1. Location of key paleomagnetic sites in relation to terrane boundaries in coastal California, Baja California, and adjacent regions. Terrane boundaries after Silberling et al. [1987] and Coney and Campa [1987]. Sites (see Table 1 for references): 1, Paleocene-Eocene German Rancho Formation near Gualala; 2, Paleocene Point San Pedro Formation near Pacifica; 3, lower to middle Eocene Butano Sandstone in Santa Cruz basin; 4, upper Upper Cretaceous Pigeon Point Formation near Half Moon Bay; 5, Jurassic (circa 155-165 Ma) Coast Range ophiolite at Stanley Mountain; 6, lower Upper Cretaceous turbidites at Fish Creek near Figueroa Mountain; 7, Upper Cretaceous Jalama Formation and Eocene strata (Poso-Canada and South Point formations) on San Miguel Island; 8, Upper Cretaceous Tuna Canyon Formation in Santa Monica Mountains; 9, Upper Cretaceous Ladd and Williams formations and Paleocene Silverado Formation at Silverado Canyon in Santa Ana Mountains; 10, San Marcos Gabbro and western Peninsular Ranges batholith in southern California (multiple sites); 11, uppermost Cretaceous (Maastrichtian) Point Loma Formation near San Diego; 12, Upper Cretaceous (Campanian) Rosario Formation near Punta San Jose; 13, upper Upper Cretaceous Punta Baja and Rosario formations near Punta Baja; 14, Peninsular Ranges batholith near San Ignacito; 15, lower Eocene redbeds and marine equivalents near Punta Rosarito; 16, Upper Cretaceous Valle Formation on Cedros Island; 17, Upper Jurassic (circa 145-155 Ma) Eugenia Formation (pillow lavas) near Punta Eugenia; 18, Upper Cretaceous Valle Formation on Vizcaino Peninsula; 19, Upper Cretaceous Valle Formation at Arroyos San Lorenzo and La Pitahaya; 20, La Paz pluton near San Bartolo; 21, Oligocene Sespe Formation in Santa Ynez Range. Major Neogene faults (see text for displacements): Elf, Elsinore; Gaf, Garlock; PMf, Pinto Mountain; Rif, Rinconada; SAf, San Andreas; SCf, San Juan-Chimeneas; SHf, San Gregorio-Hosgri; SJf, San Jacinto. Displaced terranes: BAL, Baldy (Pelona, Orocopia, and Rand schists) in solid black (underthrust Mesozoic strata); CAB, Caborca; CAT, Catalina, COR, Cortes, EP/SM, El Paso and Shadow Mountain combined (overthrust Paleozoic strata); LAP, La Paz; MAG, Magdalena; MAL, Malibu; PAR, Patton Ridge (Franciscan assemblage analogue); SAL, Salinia; SAN, Santa Ana; SNI, San Nicolas (Great Valley sequence analogue); S-O, Sur-Obisbo belt composed of San Simeon terrane (Franciscan assemblage) overlain structurally by Stanley Mountain terrane (Great Valley sequence); TUJ, Tujunga; VIZ, Vizcaino. The Santa Lucia-Orocopia allochthon (SLOA) includes BAL(?), SAL, S-O, and TUJ; the Baja-Borderland allochthon (BBA) includes CAT, part of COR, LAP, MAL, MAG, PAR, SAN, SNI, and VIZ [Champion et al., 1986; Howell et al., 1987].

dextral slip on the Rinconada fault [Graham, 1978] and 15 (to 27.5) km of dextral slip on the San Juan-Chimeneas (and Russell) fault [Bartow, 1978; Yeats et al., 1989] within the Salinian block (affects only Coast Range ophiolite at Stanley Mountain and Fish Creek turbidite site).

6. South of the Transverse Ranges, reversal of 40 km of dextral slip on the Elsinore fault [Sage, 1973] and 24 km of dextral slip on the San Jacinto fault [Sharp, 1967] in the Peninsular Ranges.

7. Within the California Continental Borderland, reversal of 195 km of dextral slip between offshore islands and the mainland (affects only Jalama, Poso-Canada, and South Point formations on San Miguel Island), as required by inferred rotation of western Transverse Ranges (see above).

These palinspastic operations to recover the pervasive imprint of Neogene tectonic transport are conservative but allow for the most significant effects of Neogene tectonism. Our conclusions are not sensitive to details of the tectonic restorations adopted because confidence limits for relevant paleomagnetic poles are large in comparison to uncertainties of the palinspastic reconstruction.

For paleomagnetic localities in pre-Tertiary rocks, speculative restoration of an additional ~150 km of dextral slip on a hypothetical Paleocene(?) proto-San Andreas fault [Dickinson, 1983] would lower reconstructed paleolatitudes by only 1° or less. We have ignored this possible Paleogene motion because the concept of a proto-San Andreas fault is controversial and incorporation of suggested proto-San Andreas slip into our reconstruction would not alter our conclusions in any substantial way. Effects of possible Cretaceous sinistral slip along the Nacimiento fault trend [Dickinson, 1983] are discussed with conclusions.

4. PENINSULAR RANGES BATHOLITH

Paleomagnetic data from a total of 32 sites are available from the combined observations of Teissere and Beck [1973] and Hagstrum et al. [1985)] for the Peninsular Ranges batholith in southern California. The mean direction is: inclination (I) = 48.7°; declination (D) = 5.9°; 95% confidence limit (α_{95}) = 3.0°. Reconstructing this region to its position prior to opening of the Gulf of California yields a mean sampling location of 31°N; 246°E. Using the mid-Cretaceous paleomagnetic pole for North America determined by Globerman and Irving [1988], the expected Cretaceous magnetic field direction at this location is: I = 60.8° ± 4.2°; D = 340.5° ± 6.6°. The expected and observed paleomagnetic directions are illustrated in Figure 3.

If present horizontal approximates paleohorizontal, the difference between the expected and observed declination indicates

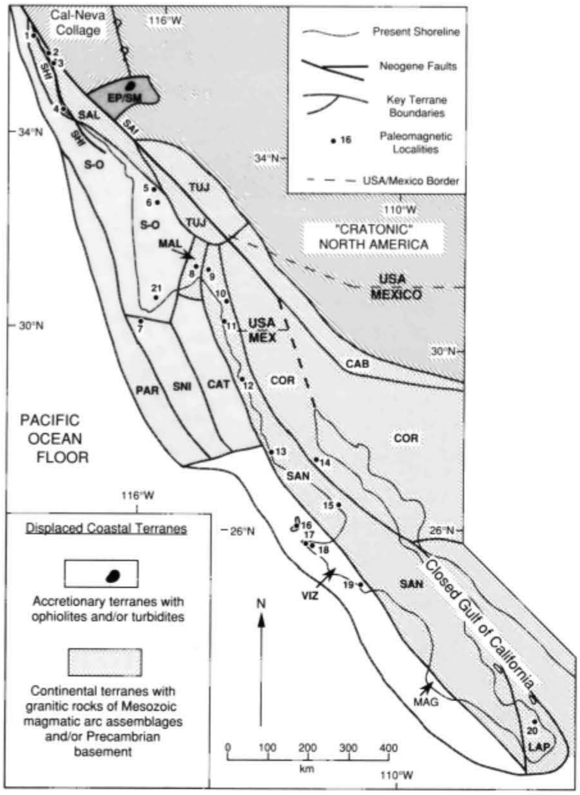

Fig. 2. Pre-Neogene palinspastic tectonic restoration (see text) of key paleomagnetic sites and terrane boundaries in coastal California and Baja California. See Figure 1 for sites (numbered 1-21) and terrane names.

~25° of clockwise tectonic rotation about a vertical axis. The difference between the expected and observed inclinations can be taken to indicate that the batholith has moved northward by ~11° of latitude with respect to interior North America. However, Figure 3 shows how tilting of the batholith can also deflect the expected direction to the observed direction. A northeast-side-up tilt of 21° about an axis with azimuth = 320° will exactly deflect the expected direction to the observed direction. Inquiry into the possibility of tilt is encouraged by limited paleomagnetic data from granitic rocks farther south in Baja California [Hagstrum et al., 1985]. Although observed declinations are discordant by ~25° at sites near San Ignacito and San Bartolo (Table 1), observed inclinations are concordant with those expected and require no northward transport of Baja California.

The obvious question is whether independent geological evidence exists to suggest that the Peninsular Ranges batholith has experienced tilting. As discussed below, we believe that such evidence is available based on metamorphic facies gradients in wall rocks, patterns of isotopic ages for granitic rocks, and paleobarometric interpretations of key mineral assemblages. Most previous workers have concluded, for example, that plutons now exposed at the surface in the eastern part of the batholith were intruded at midcrustal levels and have been uplifted greater amounts since emplacement relative to plutons of the western part of the batholith [Gastil, 1975; Krummenacher et al., 1975; Silver et al., 1979]. Following a brief summary of key arguments for differential uplift, we offer a preliminary quantitative assessment of apparent tilting.

Available paleomagnetic data were collected primarily from the western half of the batholith in southern California [Teissere and Beck, 1973; Hagstrum et al., 1985]. Coordinated K-Ar and U-Pb geochronology [Silver et al., 1979; Silver and Chappell, 1988] shows that K-Ar and U-Pb ages of granitic rocks are nearly concordant (105-120 Ma) along the western edge of the batholith but diverge progressively for collecting localities spaced towards the east. Within 50 km along a broad WSW-ENE transect the difference between U-Pb and K-Ar ages reaches approximately 25 m.y. near the middle of the batholith (i.e., 110-120 Ma for U-Pb versus 80-100 Ma for K-Ar). This contrast in the pattern of isotopic ages is interpreted to reflect differences in uplift history to bring more westerly and easterly portions of the exposed batholith to shallow crustal levels at different times. Concordant U-Pb and K-Ar ages along the western fringe of the batholith apparently reflect emplacement at comparatively shallow depths where relatively rapid cooling could close K-Ar systems shortly after the time of intrusion indicated by U-Pb ages. Discordant U-Pb and K-Ar ages farther east presumably reflect emplacement at greater depth where cooling below the blocking temperature for argon retention was delayed until tilting of the batholith had uplifted more deep-seated granitic rocks to some requisite crustal level. Across the eastern half of the batholith where no paleomagnetic data are available, patterns of isotopic ages are more complex but still imply similar tilt with progressively deeper erosion to the east. In that region a gradual eastward decrease in U-Pb ages (from ~100 Ma to ~90 Ma) along an additional 50 km of the same WSW-ENE transect is interpreted to reflect migration of magmatism. But an even greater coordinate decrease in K-Ar ages (from ~95 to ~65) is seemingly indicative of the same tilting effect. The eastward younging trend in K-Ar ages is most reasonably interpreted as the result simply of progressive cooling through the Ar retention temperature because no regionally significant heat source of ~65 Ma age is known [Krummenacher et al., 1975].

Nonisotopic methods of petrologic analysis lead to similar inferences about uplift. For example, the metamorphic grade of prebatholithic wall rocks intruded by various phases of the batholith increases progressively from WSW to ENE in the broad pattern to be expected from regional tilting [Gastil, 1975; Todd et al., 1988]. Rocks of greenschist facies along the western fringe of the batholith grade eastward to variants of amphibolite facies near the middle of the batholith and finally to migmatitic rocks along the eastern side of the batholith. Moreover, Ague and Brimhall [1988] have recently used amphibole geobarometry to determine that the depth of emplacement of the Peninsular Ranges batholith, as now exposed, ranged from 5-10 km along its western flank to 20-25 km along its eastern flank. Inferred emplacement depths within the interior of the batholith are somewhat irregular but broadly gradational between these extremes.

From the map of Ague and Brimhall [1988, Figure 7], showing the areal pattern of pressures of crystallization within the Peninsular Ranges batholith, the batholith as a whole is probably tilted an average of 12°-15° about a NNW axis. For the western half of the batholith from which available paleomagnetic data are derived, however, the widths of their isodepth bands suggest a tilt of 16° ± 4° about an axis of 340° ± 10°. Considering confidence limits for expected and observed paleomagnetic directions, the amount of tilt required to achieve

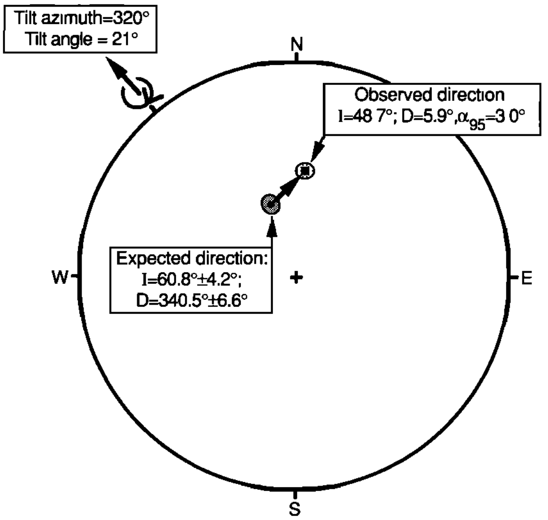

Fig. 3. Equal-area projection of observed and expected paleomagnetic direction from the Peninsular Ranges batholith in southern California. Observed direction is shown by square with surrounding stippled 95% confidence limit; expected direction is shown by circle with surrounding stippled 95% confidence limit. Tilt required to deflect expected direction to the observed direction is 21° (±5°) about an axis with azimuth 320° (±10°).

statistical concordance is 21° ± 5° about an axis of 320° ± 10°. Given the inherent uncertainties in paleomagnetic and paleobarometric data, our estimates of apparent and required tilt are in reasonably good agreement. It seems clear that present horizontal definitely does not approximate paleohorizontal for the batholith and that northeast-side-up tilting of the batholith could be primarily, if not entirely, responsible for the paleomagnetic discordance.

The tilt required by areal patterns of U-Pb and K-Ar ages within the batholith depends on paleogeothermal gradient and the degree of structural segmentation of the batholith during uplift. Neither factor is well known. For the western flank of the batholith from which available paleomagnetic data are derived, we obtain a minimum tilt estimate of 12°-15° from the following assumptions: (1) the western flank of the batholith rotated as a rigid panel ~35 km wide, (2) the ambient paleogeothermal gradient was 30°-35°C/km, and (3) blocking temperatures for retention of argon were 250°C for biotite and 525°C for hornblende (note that both are below the Curie temperature of 580°C for magnetite). General concordance of U-Pb and K-Ar ages along the western fringe of the composite batholith thus imply emplacement of plutons at a depth of ~7.5 km or less (i.e., below 250°C), whereas uniform discordance of U-Pb and K-Ar ages 35 km away near the eastern edge of the tilted crustal panel imply emplacement of plutons at depths of 15-17.5 km or more (i.e., above 525°C). The axis of tilting is constrained to lie parallel to the ~330° azimuthal trend of K-Ar age contours [Krummenacher et al., 1975]. These results are in general agreement with inferences from the independent paleobarometric data.

A minimum tilt of 12°-15° estimated from the areal pattern of isotopic ages is not quite sufficient to explain the discordant paleomagnetic directions as a result of tilting alone. However, the actual tilt reflected by isotopic age patterns could be arbitrarily larger if depths of pluton emplacement were less than the maximum inferred for the fringe of the batholith or more than the minimum inferred 35 km farther inland. Unfortunately, fission track or argon-argon data which might define the tilt more accurately are not presently available so far as we are aware.

The fact that all K-Ar ages within the batholith are >65 Ma [Krummenacher et al., 1975] suggests that the main phase of tilting, sufficient to bring all exposed granitic rocks to shallow crustal levels, occurred during Late Cretaceous time and was completed by the end of Cretaceous time. This Cretaceous episode of tilting can be ascribed to greater isostatic recovery and deeper erosion eastward in response to greater crustal thickening in that direction during formation of the batholith [Silver et al., 1979]. Given the total range (90-120 Ma) of U-Pb ages for granitic rocks of the batholith [Silver et al., 1979; Silver and Chappell, 1988], intrusion evidently spanned an interval of mid-Cretaceous time (Aptian to Cenomanian), with more westerly plutons emplaced earlier and at shallower depth than more easterly ones. Basal horizons of unconformably overlying strata that cap Cretaceous erosion surfaces along the western edge of the batholith range in age from Turonian to Campanian [Todd et al., 1988]. Initiation of deposition thus occupied a time interval (80-90 Ma) closely following batholith emplacement, and some component of batholith tilt doubtless affected capping strata as well.

Variable seaward dips of unconformably overlying cover strata apparently record effects of locally intense deformation as well as continued regional tilting. For example, thick Upper Cretaceous strata of Turonian to Campanian age (80-90 Ma) in the Santa Ana Mountains [Schoellhamer et al., 1954, 1981], between Los Angeles and San Diego, dip 30°-35° westward about a mean strike of ~340° where they rest depositionally upon wall rocks of the batholith, and overlying Paleogene strata dip just as steeply nearby. However, equivalent and younger strata farther south near the coast dip more gently seaward at 5°-10° [Gastil et al., 1973]. More detailed and informed analysis of areal patterns of dip magnitudes than we are able to attempt will be required to separate effects of local deformation from regional tilt and to establish the timing of each. A widespread erosion surface of gentle relief had developed over much of the Peninsular Ranges by Paleogene time, but the youngest component of regional tilt probably accompanied development of a westward sloping rift shoulder parallel to the Neogene spreading centers of the Salton Basin and Gulf of California [Silver et al., 1979].

5. JURASSIC VOLCANIC ROCKS

We compiled and analyzed all published paleomagnetic data (based on sampling of at least four igneous cooling units or four individual beds of sedimentary units) from Mesozoic through Oligocene layered rocks of the Santa Lucia-Orocopia (SLOA) and the Baja-Borderland (BBA) allochthons (suspect terranes of Figure 1). We required that the age of the rock unit be known within ±10 m.y. Only paleomagnetic data from the Jurassic Bedford Canyon Formation [Morris et al., 1986] were excluded due to insufficient age resolution. Rock units were reconstructed to their respective paleogeographic positions according to the procedures discussed above. These positions are listed in Table 1 and were used to compute the expected directions of paleomagnetism from the applicable reference pole. Details of the calculations of paleolatitudes and implied northward transport are presented in the appendix. Results of our compilation and analysis are presented in Table 1 and in Figure 4 and are discussed below.

5.1. *Jurassic Paleomagnetic Reference Poles*

Previous analyses of the Jurassic paleomagnetic data from SLOA and BBA used reference paleomagnetic poles from the compilation of Irving and Irving [1982]. More recent analyses of Mesozoic North American apparent polar wander (APW) have been presented by Gordon et al. [1984] and by May and Butler [1986]. Both analyses indicate that North America was at lower paleolatitudes during the Jurassic than indicated by the APW path of Irving and Irving [1982]. The expected paleolatitudes calculated here are thus substantially lower than those previously determined.

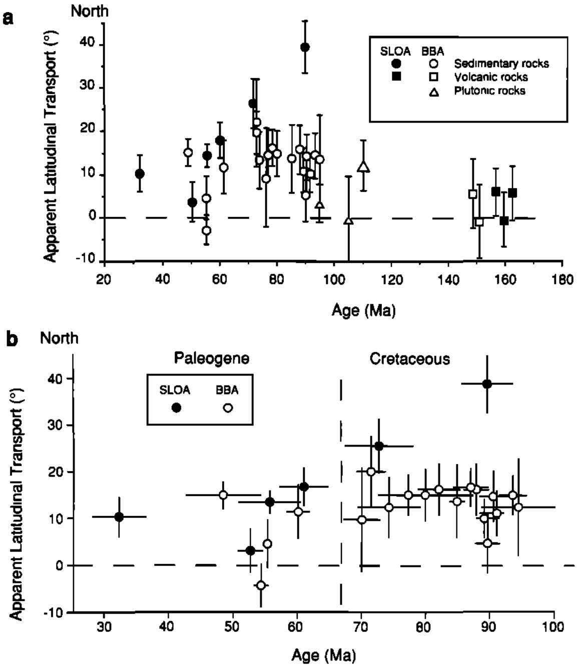

Fig. 4. (a) Apparent northward transport of the Santa Lucia-Orocopia allochthon (SLOA) and the Baja-Borderland allochthon (BBA) versus age of geologic unit from which paleomagnetic data were acquired (Table 1). Inset gives labels for lithology and allochthon of geologic units. Vertical error bars are 95% confidence limits on apparent latitudinal transport. For clarity of error bars, some points have been plotted slightly removed from the ages listed in Table 1. Multiple points calculated for volcanic rocks of the Coast Range ophiolite and the Eugenia Formation show the effect of using different paleomagnetic reference poles listed in Table 1. (b) Apparent northward transport determined from Cretaceous and Paleogene sedimentary rocks of SLOA and BBA (Table 1). Range of age is indicated by the horizontal bar through each data point.

It is important to point out that there are differences between the analyses of Jurassic APW presented by Gordon et al. [1984] and by May and Butler [1986]. Gordon et al. [1984] fit their selection of paleomagnetic poles to a paleomagnetic Euler pole (PEP) model. They conclude that the current best determinations of paleomagnetic reference poles for North America are found by their best fit PEP model APW path. Alternatively, May and Butler [1986] applied stringent selection criteria to the available paleomagnetic poles and allowed the space-time pattern of the selected poles to determine the APW pattern. The individual selected poles are thought to provide the best available reference paleomagnetic poles.

Differences between the reference paleomagnetic poles proposed by Gordon et al. [1984] and by May and Butler [1986] are largest in the Middle and Late Jurassic. For example, the Eugenia Formation has an age of ~150 Ma, and the appropriate reference pole according to Gordon et al. [1984] would be their PEP 150 Ma pole. But the appropriate reference pole according to the May and Butler [1986] analysis would be the pole from the 151 ± 2 Ma Glance Conglomerate. These two different reference poles predict paleolatitudes for the Eugenia Formation which are 7° different. To allow the effect of choice of reference paleomagnetic pole to be evident in our analysis, we have computed expected paleolatitudes using plausible alternative reference poles. Results are listed in Table 1 and are discussed below.

5.2. *Jurassic Volcanic Rocks of SLOA and BBA*

The only available paleomagnetic data from Mesozoic volcanic rocks are those from the Jurassic Eugenia Formation of the Vizcaino terrane in Baja California and from the Coast Range ophiolite of the Stanley Mountain terrane in central California. These volcanic rocks are part of BBA and SLOA assemblages, respectively, and are overlain by Cretaceous marine sediments. McWilliams and Howell [1982] and Hagstrum et al. [1985] interpreted the characteristic paleomagnetism of these rocks as a primary thermoremanent magnetism. Because volcanic rocks are potentially accurate recorders of paleolatitude, previous interpretations of northward transport based on paleomagnetic data from the Coast Range ophiolite and the Eugenia Formation have been considered robust.

The Coast Range ophiolite is dated at ~160 Ma. McWilliams and Howell [1982] determined an expected paleolatitude of >30° for the Coast Range ophiolite and inferred a minimum of ~15° of northward transport. But revised Jurassic APW paths indicate an expected paleolatitude of 14° to 21° (with uncertainty of ~5°; see Table 1), depending on the choice of reference paleomagnetic pole (Table 1; Figure 4a). The expected paleolatitude is thus in close proximity to the observed paleolatitude of 14.3 ± 4.8°. This result indicates little or no net latitudinal motion of the Stanley Mountain terrane since 160 Ma. Moreover, a fundamental uncertainty in interpretation of the paleomagnetic results from the Coast Range ophiolite has recently been introduced. Hagstrum [1990] has suggested that these rocks were remagnetized long after deposition, possibly in Late Cretaceous time. If this suggestion is substantiated, then paleohorizontal at the time of magnetization is not directly known and interpretation of the paleomagnetic data becomes problematical. The original interpretation of ~15° of post-Late Jurassic northward transport of the Stanley Mountain terrane is in doubt. If the magnetization is original, the paleolatitude is concordant (or near concordant); if the magnetization is secondary, the interpretation is uncertain.

The Eugenia Formation is dated at ~150 Ma. The observed paleolatitude of 13.5° ± 8.6° agrees with the expected paleolatitudes of 11.6° or 18.7° resulting from the choices of reference paleomagnetic pole (Table 1; Figure 4a). This result indicates little or no net latitudinal motion of the Vizcaino terrane since 150 Ma. However, J. J. Hagstrum (written communication, 1990) cautions that structural attitudes of pillow lavas in the Eugenia Formation are difficult to determine with attendant uncertainty in structural correction to the observed paleomagnetic directions. In addition, the number of independent cooling units sampled may be only two so that uncertainties in the mean paleomagnetic direction may be very large. Quite clearly the paleomagnetic data from the Eugenia Formation cannot be taken as an indication of post-Late Jurassic northward transport. If the mean paleomagnetic direction is accurate, the paleolatitude is concordant and no northward transport is required.

Based solely on the paleomagnetic observations, southern hemisphere origins of the Eugenia Formation and the Coast Range ophiolite are technically possible. However, in keeping with our attempt to explain the paleomagnetic data without large-scale transport, we do not entertain this possibility.

6. CRETACEOUS AND PALEOGENE SEDIMENTARY ROCKS

6.1. *Paleomagnetic Data From SLOA and BBA*

Figure 4b illustrates the apparent latitudinal transports of SLOA and BBA indicated by paleomagnetic data from Upper Cretaceous and Paleogene sedimentary rocks. For the Santa Lucia-Orocopia allochthon the apparent latitudinal transport shows a roughly linear decrease with time from mid-Cretaceous to Eocene. This well-defined trend has been interpreted as the latitudinal motion trajectory of SLOA prior to Eocene accretion. However, this interpreted motion history is severely compromised by the ~10° of latitudinal transport required by literal interpretation of the paleomagnetic inclination of the Oligocene Sespe Formation. Taking the interpreted paleolatitudinal motion history at face value requires (1) 40° of northward translation between 90 Ma and the 52 Ma age of the Butano Sandstone, which has a concordant paleolatitude, (2) 10° of southward translation between 52 Ma and the 32 Ma age of the Sespe Formation, and (3) 10° of northward translation to place SLOA in position for subsequent Neogene deformation by the San Andreas fault system.

The overall pattern of apparent latitudinal motion history of BBA has important elements in common with that of SLOA. There is a general grouping of observations from Cretaceous and Paleogene marine sedimentary rocks indicating apparent latitudinal transports of ~15°. However, one section of the Cretaceous Valle Formation of the Vizcaino terrane yields a concordant paleolatitude while other sections of the Valle Formation indicate apparent transports of ~15°. A more serious inconsistency is presented by paleomagnetic data from intertonguing marine and continental sedimentary rocks of early Eocene age in the Punta Prieta region of the Santa Ana terrane in Baja California [Flynn et al., 1989]. Both the marine and continental sedimentary rocks there yield concordant paleolatitudes while coeval or younger Eocene marine sedimentary rocks (Poso-Canada and South Point formations) on San Miguel Island of the San Nicolas terrane indicate ~15° of northward translation. Again, a literal interpretation of the paleolatitudes inferred from the paleomagnetism of sedimentary rocks requires a complex north-then-south-then-north latitudinal motion history for BBA.

The continental sedimentary rocks in the Punta Prieta region are red sediments of the Las Tetas de Cabra Formation. The blocking temperatures observed by Flynn et al. [1989] suggest that a significant portion of the paleomagnetism is carried by hematite. We speculate that the characteristic paleomagnetism of the Las Tetas de Cabra Formation could be a chemical remanent magnetism acquired during hematite cementation of these continental deposits. If this speculation is correct, the paleomagnetic direction in these cemented continental deposits may not be susceptible to compaction shallowing of paleomagnetism which has likely affected many of the marine sedimentary rocks of SLOA and BBA. However, counter to this suggestion is the observation of discordant shallow inclinations in red sediments of the Oligocene Sespe Formation which also exhibit blocking temperatures exceeding 600°C [Liddicoat, 1990].

Additional geological evidence suggests that Paleogene strata of the Poso-Canada and South Point formations in the Channel Islands cannot be far traveled with respect to North America. Exposures of these formations among the islands are stratigraphically associated with Eocene marine conglomerates of the Jolla Vieja Formation containing distinctive rhyolitic clasts also present in correlative fluvial conglomerates of the mainland Poway Group [Kies and Abbott, 1983]. Well-documented Neogene lateral offset of Paleogene depositional systems shows that conglomeratic strata exposed in the Channel Islands were deposited just offshore from present occurrences of Poway strata at San Diego [Howell and Link, 1979]. Geochemical comparisons of characteristic Poway-type clasts with bedrock exposures have successfully identified a potential source in outcrops of Jurassic metavolcanic rocks of northern Sonora, inboard of all identified suspect terranes [Abbott and Smith, 1978, 1989]. The fluvial dispersal system that transported the distinctive clasts westward has been disrupted by Neogene strike slip, but any greater tectonic transport of Paleogene rocks on San Miguel Island is seemingly precluded by the presence of the distinctive Poway-type clasts.

In addition to the complex motion histories required by the interpreted paleolatitudinal histories for SLOA and BBA, the growing paleomagnetic data base has led to difficult traffic problems between the allochthons. When few data were available, simple motion histories were interpreted for SLOA [McWilliams and Howell, 1982; Champion et al., 1984]. However, as more data have been acquired from both allochthons, complex traffic patterns have developed in more recent interpretations [e.g., Champion et al., 1986, Figure 17; Howell et al., 1987, Figure 10-6]. In these latter interpretations the following motion sequence takes place: (1) SLOA is placed at more southerly Cretaceous paleolatitudes than BBA; (2) SLOA experiences rapid northward transport in Late Cretaceous and Paleogene time (during this motion, SLOA passes the inboard BBA in the Paleocene and arrives at its pre-Neogene location by early Eocene time); (3) BBA then experiences ~15° of northward transport between Eocene and early Miocene time. Even this complex motion history does not account for the inconsistencies discussed above.

6.2. *Inclination Shallowing in Sedimentary Rocks*

Paleomagnetism resulting from deposition and consolidation of sedimentary rocks in the geomagnetic field is detrital remanent magnetism (DRM). Alignment processes occurring at the time of deposition produce "depositional" DRM while alignment processes taking place between deposition and consolidation result in "postdepositional" DRM (pDRM) (see review by Verosub [1977]). A long-standing concern of paleomagnetists is the accuracy of DRM in recording the geomagnetic field direction.

It is known that the inclination of depositional DRM is often systematically shallower than the inclination of the magnetic field present during deposition. This is the classic "inclination error" of DRM originally observed in glacial deposits [King, 1955]. Inclination of resulting DRM, I_o, was found to be systematically shallower than inclination of the magnetic field, I_H, to which it was related by:

$$\tan I_o = f \tan I_H \tag{1}$$

The value of f in (1) was 0.4 for redeposited glacial sediments. However, postdepositional processes dominate magnetization of many sediments, especially fine-grained and/or bioturbated sediments. Magnetic particles suspended in slurry-like wet clays are evidently able to rotate into alignment with the ambient magnetic field.

The two natural examples most often cited as evidence for absence of inclination error in pDRM are (1) paleomagnetism of Holocene lake sediments [Lund, 1985] and (2) paleomagnetic records from Pliocene-Pleistocene deep-sea cores [Opdyke and Henry, 1969]. In both cases, large data sets clearly indicate that pDRM of these young unconsolidated sediments accurately records the geomagnetic field direction. These examples demonstrate that fine-grained sediments with magnetization dominated by pDRM processes and buried by a few meters of overlying sediments do not possess inclination error.

An influential example of accurate paleomagnetic inclinations in Paleogene turbidites was provided by paleomagnetic observations in the Oregon Coast Range. Eocene turbidites of the Tyee and Flournoy formations are bracketed by the older (~55 Ma) Siletz River Volcanics and the younger (~45 Ma) Yachats basalt. Simpson and Cox [1977] demonstrated that the paleomagnetic inclination shows no significant variation through this stratigraphic sequence. The Tyee and Flournoy formations quite clearly do not have a shallowed paleomagnetic inclination. However, more recent observations suggest that the Oregon Coast Range turbidites may be an exception to the general rule of compaction shallowing of paleomagnetic inclination in turbidites. As the following discussion indicates, mechanisms for compaction shallowing of inclination are not well understood, nor are the fabrics of Tyee-Flournoy mudrocks known well enough to specify how their properties may differ from seemingly comparable strata in which varying amounts of compaction shallowing are evident.

Recent laboratory experiments suggest that interactions between fine-grained magnetite and clay particles may be important in controlling compaction shallowing of inclination [Anson and Kodama, 1987; Deamer and Kodama, 1990]. Small elongate magnetite particles apparently adhere to clay particles and are rotated towards the bedding plane during compaction. If DRM or pDRM behaves as a passive line marker during subsequent compaction, the inclination of DRM or pDRM will shallow according to (1) where f is the ratio of compacted to original thickness. A number of well-documented cases of compaction shallowing of paleomagnetism in both continental and marine sediments have recently become available.

Butler and Taylor [1978] presented the results of extensive paleomagnetic investigations of continental sediments of the Paleocene Nacimiento Formation in the San Juan Basin, New Mexico. Paleomagnetic data from 104 stratigraphic levels pass the reversals test and the mean direction has a 95% confidence limit of 3.0°. But the mean inclination is 8° shallower than predicted by the well-established paleomagnetic pole derived from Paleocene igneous rocks in Montana [Diehl et al., 1983; Gordon, 1984]. This shallowing of inclination (implying spurious northward transport of the San Juan Basin by 7° ± 3° of latitude since 60 Ma) is almost certainly the effect of compaction.

Recent results from DSDP cores indicate that a wide variety of marine sediments are also subject to compaction shallowing of paleomagnetic inclination. Arason and Levi [1990] have shown a 6°-8° shallowing of inclination in the upper 100 m of sediment from DSDP site 578 in the northwest Pacific. The oldest sediments sampled were only ~6 Ma. Celaya and Clement [1988] observed shallowed inclinations in Miocene to Recent DSDP cores from the North Atlantic. Tarduno [1990] and Gordon [1990] analyzed extensive paleomagnetic data from Cretaceous sediments in DSDP cores from the western Pacific. Observed inclinations of stable paleomagnetism were compared with inclinations predicted by the APW path of the Pacific plate (determined from analyses of marine magnetic anomalies and seamount magnetic anomalies). A clear bias towards shallow inclination was observed. Consistent with (1), Tarduno [1990] found maximum shallowing for an expected inclination of 55°. A mean value of 0.52 was determined for f in (1), with lower and upper confidence limits of f = 0.23 and f = 0.80. The only sediment type which did not show inclination shallowing was silicified limestone. Turbiditic and nonturbiditic sediments were similarly affected by compaction shallowing of inclination.

Coe et al. [1985] compared paleomagnetic data from Late Cretaceous and early Tertiary lavas and turbidites of several tectonostratigraphic terranes in Alaska. Paleomagnetic inclinations were found to be systematically shallower in the sedimentary rocks. The most dramatic comparison is from the Prince William and Chugach terranes where paleolatitudes calculated from paleomagnetic inclinations in the turbidites are ~30° lower than paleolatitudes determined from the paleomagnetic inclinations in associated lavas. Coe et al. [1985] showed that the paleolatitudinal error resulting from inclination error is given by

$$\Delta\lambda = \lambda - \tan^{-1}(f \tan \lambda) \tag{2}$$

where $\Delta\lambda$ is paleolatitudinal error, λ is paleolatitude, and f is the inclination error factor of equation (1). A value of $f \approx 0.4$ is consistent with the paleolatitudinal errors observed in the Alaskan turbidites. It is worth noting that many of these Alaskan turbidites are strongly deformed, and the shallowed inclinations may have been produced by deformational effects as well as by simple burial.

It is clear from the above discussion that some sediments have paleomagnetic inclination errors of substantial magnitude while others do not. Undoubtedly, many sedimentological, diagenetic, and/or deformational factors control inclination shallowing (or lack thereof) in a particular sediment. These factors are not yet understood, and it is not possible to predict the presence or absence of inclination error based on lithologic characteristics. Thus we do not have direct evidence that any of the paleomagnetic inclinations of the marine sediments of SLOA or BBA contain inclination error. However, the available information does suggest that (unless cemented soon after deposition) the majority of fine-grained sedimentary rocks which have undergone significant compaction will have shallowed paleomagnetic inclinations.

We can investigate whether inclination error is a plausible explanation of the paleomagnetic observations from SLOA and

BBA by the following calculation. The apparent latitudinal transport indicated by paleomagnetic data on Cretaceous and Paleogene marine sediments of the Baja-Borderland allochthon is ~15° (Figure 4b). The expected paleolatitudes listed in Table 1 have an average value of ~40°. Using $\Delta\lambda = 15°$ and $\lambda = 40°$ in (2) yields $f = 0.55$ as the mean inclination error factor required to account for the paleomagnetic observations. This value is in good agreement with the $f = 0.52$ value determined by Tarduno [1990] from Cretaceous DSDP cores and is larger (less flattening of inclination) than that determined by Coe et al. [1985] for Alaskan turbidites. The magnitude of inclination shallowing required to account for the paleomagnetic data from the Baja-Borderland allochthon is thus consistent with magnitudes of inclination shallowing demonstrated in marine sediments of similar age and lithology. Moreover, a roughly constant compaction shallowing of inclination in these sedimentary rocks would yield the observed track of paleolatitudes consistently offset towards more southerly paleolatitudes compared with the cratonic paleolatitude trajectory [e.g., Morris et al., 1986; Champion et al., 1986].

Figure 5 graphically illustrates that the amount of compaction shallowing required to explain the paleolatitudinal discordance of marine sedimentary rocks of SLOA and BBA is consistent with the observations on Cretaceous deep-sea sediments of the Pacific plate. Although the scatter is large, the observations from Cretaceous and Paleogene sediments of SLOA and BBA are quite consistent with the amounts of compaction shallowing demonstrated for Pacific deep-sea sediments.

7. DISCUSSION AND CONCLUSIONS

7.1. *Conclusions*

A gross ranking of accuracy of paleomagnetic directions from major rock types would place volcanic rocks as the most reliable paleomagnetic recorders. With the caveat that paleohorizontal is often ambiguous, intrusive rocks would be placed below volcanic rocks and probably above sedimentary rocks. We organize our conclusions in this order, which is also the general age progression of the supposedly allochthonous rocks from which paleomagnetic data are available.

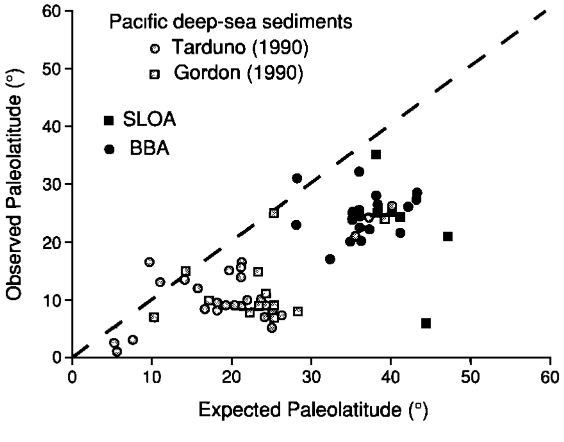

Fig. 5. Comparison of predicted and observed paleolatitudes for marine sedimentary rocks. Paleolatitudes from mean paleomagnetic inclinations of Pacific deep-sea sediment cores are compared with paleolatitudes predicted from the apparent polar wander path for the Pacific plate [Gordon, 1990; Tarduno, 1990]. Paleolatitudes from paleomagnetism of SLOA and BBA sedimentary rocks are compared with paleolatitudes predicted from the North American apparent polar wander path at reconstructed positions of rock units prior to Neogene deformation (Table 1).

The concordant paleolatitudes determined from the Jurassic Eugenia Formation of BBA and the Coast Range ophiolite of SLOA are important observations. Although some variation in predicted paleolatitude results from the choice of paleomagnetic reference pole, all acceptable reference poles yield concordant or nearly concordant paleolatitudes. Further questions have arisen about the accuracy of mean paleomagnetic directions from these Jurassic volcanic rocks and possibly about the age of magnetization. Certainly the paleomagnetic data from the Jurassic volcanic rocks of SLOA and BBA can no longer be taken as evidence for large-scale northward transport.

A major appeal of the large-scale northward transport interpretation of discordant paleomagnetic directions from SLOA and BBA has been the perceived internal consistency of results between sedimentary and plutonic rocks. Certainly there is internal consistency of discordant paleomagnetic directions from the southern California portion of the Peninsular Ranges batholith [Teissere and Beck, 1973; Hagstrum et al., 1985]. This consistent discordant paleomagnetic direction indicates major tectonic disturbance subsequent to magnetization of these rocks. However, we conclude that the discordant paleomagnetic direction was produced by tilting of the batholith rather than by large-scale northward tectonic transport. With the discordant paleomagnetic directions from the Peninsular Ranges batholith explained by tilting, the major case for internal consistency of results between the sedimentary and plutonic rocks is removed.

A consistent sense and amount of clockwise vertical axis rotation is often used as an argument for large-scale northward transport and clockwise vertical axis rotation of SLOA and BBA [Hagstrum et al., 1985; Filmer and Kirschvink, 1989]. But a close examination of the vertical axis rotations reveals important inconsistencies in sense and amount of rotation. Figure 6 illustrates vertical axis rotations inferred from paleomagnetic studies of Mesozoic and Paleogene units located between the western Transverse Ranges and the Vizcaino Peninsula. The majority of results indicate varying amounts of clockwise vertical axis rotation. However, important exceptions include the following: (1) The Valle Formation at various localities on the Vizcaino Peninsula (points 16, 18, and 19 of Figure 6) shows vertical axis rotations ranging from 21.6° ± 9.7° counterclockwise to 33.7° ± 9.0° clockwise. (2) The Eocene Bateque Formation (point 15 of Figure 6) shows counterclockwise rotation of 18.7° ± 6.9°. (3) In the crustal block of the Santa Ana terrane containing the southern California portion of the Peninsular Ranges batholith the Late Cretaceous Ladd and Williams formations and the Paleocene Silverado Formation show counterclockwise rotations of 16.8° ± 9.4° and 17.6° ± 10.2°, respectively. As more paleomagnetic data have been acquired, the initial impression of consistent clockwise rotation by ~25° (suggesting coherent rotation of major portions of SLOA and BBA) has given way to a more complex pattern of vertical axis tectonic rotations. Certainly the pattern of vertical axis rotations provides important information about the tectonic development of southern and Baja California. But the appeal of large-scale northward transport coupled with clockwise vertical axis rotation has deteriorated significantly.

The influence of vertical axis tectonic rotations on the present orientations of paleomagnetic vectors measured for the tilted batholithic rocks is uncertain. From Figure 6 we infer

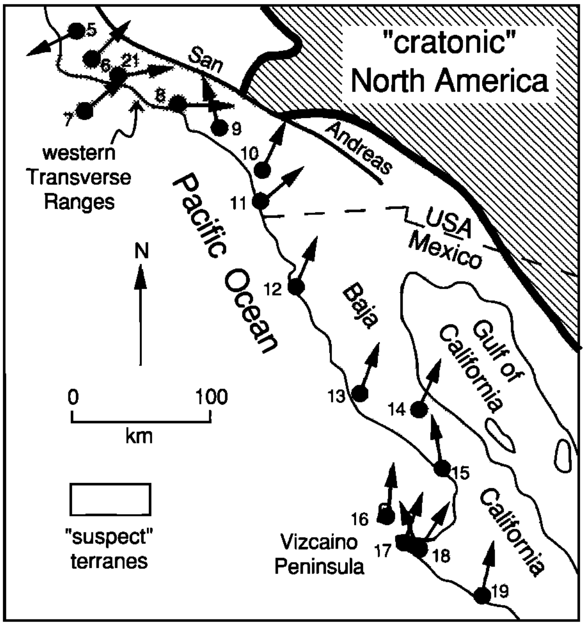

Fig. 6. Inferred vertical axis rotation from paleomagnetic declinations. Arrows indicate the rotation of the observed mean paleomagnetic declination relative to expected declination of due north. Results are shown for paleomagnetic studies of Jurassic, Cretaceous, and Paleogene rocks between the western Transverse Ranges and the Vizcaino Peninsula. Numbered sites are keyed to Figure 1 and Table 1.

that the tilt effect is dominant for two reasons: (1) With respect to each of the two paleomagnetic sites for batholithic rocks (points 10 and 14 of Figure 6), the two nearest paleomagnetic sites for sedimentary rocks (points 9 and 11 and points 13 and 15, respectively) show both clockwise and counterclockwise apparent rotations, whose calculated resultants would be small and of dubious actual significance. (2) The vector mean of apparent tectonic rotation indicated by data for sedimentary rocks at all paleomagnetic sites south of the Transverse Ranges (Figure 6) is only about 6° clockwise. This value is probably well within the uncertainty envelope for regional interpretations, given the inherent variability of the data and the wide sample spacing (averaging one site per 50 km of distance).

With the Jurassic volcanic rocks of BBA and SLOA yielding concordant paleolatitudes and the discordant paleomagnetic directions from the Peninsular Ranges batholith in southern California explained by tilting, the case for large-scale northward transport rests on paleomagnetic data from Upper Cretaceous and Paleogene marine sedimentary rocks. At least for BBA, paleolatitudes determined from these rocks are generally ~15° south of adjacent portions of North America. As discussed above, major problems arise from literal interpretation of paleolatitudes determined from the sedimentary rocks. Concordant paleolatitudes are indicated by some sedimentary rocks, while other coeval or younger sedimentary rocks of the same allochthon imply major latitudinal transport. Literal interpretation of the paleolatitudes from the sedimentary rocks requires large-scale north-then-south-then-north transport of SLOA and BBA and a complex motion history between the two allochthons.

Given the increasing evidence for compaction shallowing of paleomagnetic inclination in a wide variety of marine sedimentary rocks and the major problems posed by paleolatitudinal interpretations of their paleomagnetism, we conclude that Upper Cretaceous and Paleogene marine sedimentary rocks of SLOA and BBA have also undergone compaction shallowing of paleomagnetic inclination. Paleolatitudes determined from these sedimentary rocks are thus systematically biased towards low paleolatitudes. However, we admit that this conclusion is largely inferred from perceived inconsistencies and complexities of the paleolatitudinal history of SLOA and BBA derived from the sedimentary rocks. Whereas our conclusions of concordant paleolatitudes from the Jurassic volcanic rocks and tilting of the Cretaceous plutonic rocks are based on direct evidence, no similar direct evidence exists to support the inference that compaction has shallowed paleomagnetic inclinations in the marine sedimentary rocks of SLOA and BBA.

Our major overall conclusion is that paleomagnetic observations from SLOA and BBA do not require large-scale post-mid-Cretaceous northward transport of coastal California or Baja California relative to interior North America. Instead, we conclude that all discordant paleomagnetic inclinations are explained by tilting of granitic plutons about subhorizontal axes or by compaction shallowing of paleomagnetic inclinations in marine sedimentary rocks. We thus interpret the Mesozoic and Cenozoic rocks of SLOA and BBA as integral parts of the western continental margin of North America rather than as far-traveled allochthonous terranes.

Speculative restoration of 550-575 km of Cretaceous sinistral strike slip along the Nacimiento fault flanking the Salinian block on the west, as suggested by Dickinson [1983], cannot be tested adequately with available paleomagnetic data. For example, if hypothesized Nacimiento slip is used in the tectonic restoration, the tilt required to make paleomagnetic directions concordant within the Peninsular Ranges batholith of southern California would change from 21° about an axis of 320° to 22° about an axis of 315°. No such minor effect could ever be reliably detected.

7.2. *Puzzling Coincidences*

Although our interpretations provide an appealing reconciliation of the available paleomagnetic and geologic data, some puzzling observations remain largely unexplained. The most striking of these are (1) the near coincidence in amounts of paleolatitudinal discordance for BBA which we ascribe to tilting of the Peninsular Ranges batholith on the one hand and to compaction shallowing of paleomagnetic inclinations of sedimentary rocks on the other, and (2) the linear dependence of paleolatitude discordance for SLOA on age of the sedimentary rock units from mid-Cretaceous to Eocene.

We argued above that in conjunction with isotopic and petrologic data the observed discordant paleomagnetic direction from the Peninsular Ranges batholith in southern California was best explained by northeast-side-up tilting of the batholith. In reasonable agreement with geologic evidence suggesting a tilt of 15°-20° about an axis with azimuth ~330°-340°, the discordant paleomagnetic direction can be explained by a tilt of 21° ± 5° about an axis with azimuth 320° ± 10°. Although paleomagnetic data from other regions of the batholith are meager, the tilts required to explain the discordant directions from those areas are similar. The discordant paleomagnetic direction observed from the batholith near San Ignacito (location 14 of Figure 1) in northern Baja California requires a tilt of ~17° about an axis with azimuth ~341°; the required tilt near La Paz (location 20 of Figure 1) in southern Baja California is ~20° about an axis with azimuth ~357°.

Considering inherent uncertainties, a common westward tilt of the whole peninsula by 15°-20° about its NNW longitudinal axis is indicated, perhaps as multiple fault-bounded panels rather than in wholesale fashion. We suspect that this consistent tilt reflects the combined effects of two influences: (1) consistently greater uplift of the deep easterly keel of the batholith during Cretaceous time, and (2) fairly uniform westerly slope of the Tertiary rift shoulder associated with opening of the Gulf of California and emplacement of oceanic crust along its trend.

Beyond the challenge of understanding a regionally consistent tilt of the Peninsular Ranges batholith, our interpretation requires that tilt of the batholith in southern California yield an apparent ~11° paleolatitudinal discordance uncomfortably similar to the apparent ~15° paleolatitudinal discordance resulting from compaction shallowing of inclination in a majority of the Cretaceous and Paleogene marine sedimentary rocks of BBA (Figure 4). We must argue that the flattening parameter ($f \approx 0.55$) characteristic of the sedimentary rocks yields inaccurate paleolatitudes which mimic the effects of pluton tilt. However, the degree of this coincidence should not be overstated, as there is much scatter in the amount of apparent latitudinal transport indicated by the paleomagnetic data from the sedimentary rocks (see Figure 4).

Just as some puzzling coincidences can be taken as arguments against our interpretation, other coincidences result from the interpretation of large-scale northward transport. One such puzzling coincidence surrounds the paleomagnetic observations from Jurassic volcanic rocks of the Coast Range ophiolite (Stanley Mountain terrane). Although originally interpreted as a primary magnetization [McWilliams and Howell, 1982], the possibility has been advanced that these rocks were remagnetized, perhaps in Cretaceous time. Hagstrum [1990] has argued that paleohorizontal at the time of remagnetization can be inferred from geologic relations. When restored to this inferred Cretaceous paleohorizontal, the observed paleomagnetic direction is discordant when compared to an expected Cretaceous magnetic field direction. This discordance is then used to argue for large-scale post-Cretaceous northward transport of the Stanley Mountain terrane. We showed above that the observed paleomagnetic directions in the Coast Range ophiolite yield a concordant paleolatitude when compared with Jurassic North American paleolatitudes. The interpretation of paleomagnetic directions from the Coast Range ophiolite as a Cretaceous remagnetization (with subsequent large-scale northward transport) requires a startling coincidence. These rocks must be remagnetized during the Cretaceous at a location and a structural attitude so that the paleomagnetic direction mimics a primary Jurassic magnetization with a concordant paleolatitude.

As discussed above, apparent latitudinal transport for SLOA shows a linear decrease with time (see Figure 4b). In the large-scale northward transport model, this trend is interpreted as the latitudinal motion trajectory of SLOA prior to Eocene accretion. We believe the case for compaction-shallowed paleomagnetic inclinations in the Cretaceous and Paleogene sedimentary rocks of SLOA and BBA is strong, if admittedly circumstantial. However, our interpretation requires us to argue that the apparent trajectory of paleolatitudes from SLOA is the effect of increased compaction (and/or deformational) shallowing of paleomagnetic inclination in progressively older marine sedimentary rocks of this allochthon. Although it is true that the likely amount of burial and deformation increases with age for these sedimentary rocks, we are uneasy with this explanation of the linear trend of paleolatitudes determined from sedimentary rocks of SLOA. No similar trend is evident in the paleolatitudes determined from sedimentary rocks of BBA. We look forward to further paleomagnetic and geologic research which will shed light on these puzzling coincidences.

APPENDIX

Paleolatitudes determined from the observed paleomagnetic direction of each rock unit are listed in Table 1. The observed paleomagnetic directions are interpreted by the original authors as primary magnetizations dating from the age of the sampled rock units. Accordingly, the paleolatitudes were determined from the structurally corrected paleomagnetic directions. Paleolatitudes were determined by one of three methods:

1. Paleolatitudes (and attendant 95% confidence limits) were taken from the original publication when the analysis could not be repeated with the data given. Included in this category are results from Pigeon Point, Point San Pedro, German Rancho Formation, Poso and Canada Formations, and the Butano Sandstone. We have no reason to question the calculations of these paleolatitudes listed in the original publications, and we accept them at face value.

2. Paleolatitudes were generally calculated from the mean paleomagnetic direction listed in the original publication. When sufficient data were presented, we recalculated the mean direction from the site mean directions. All paleolatitudes calculated in this fashion agreed with those listed in the original publications within 0.1°.

In detail, confidence limits on paleolatitudes determined from mean paleomagnetic directions are asymmetric about the mean paleolatitude. However, following the procedure used in most of the original publications, we approximated the 95% confidence limits on paleolatitudes using

$$d\lambda = \frac{\lambda_o^+ - \lambda_o^-}{2} \tag{3}$$

where

$$\lambda_o^+ = \tan^{-1}\left(\frac{\tan[I_o + \alpha_o]}{2}\right); \tag{4}$$

$$\lambda_o^- = \tan^{-1}\left(\frac{\tan[I_o - \alpha_o]}{2}\right); \tag{5}$$

I_o is the observed mean paleomagnetic inclination, and α_o is the 95% confidence limit on mean paleomagnetic direction. The confidence limits listed in Table 1 agree with those given in the original publications within 0.2°.

3. For some studies, site mean virtual geomagnetic poles (VGPs) could be used to calculate an observed paleomagnetic pole. This procedure was used for the paleomagnetic data reported by Hagstrum et al. [1985] for the Eugenia and Valle formations. Paleolatitudes were then determined from the paleomagnetic poles and were within 0.1° of those listed in the original publication.

The paleomagnetic reference poles for interior North America are listed in Table 1. These poles are used to determine the expected paleolatitude of each rock unit in its reconstructed location. For the Cretaceous and Tertiary these reference poles are fairly well established. For Tertiary units the expected paleolatitudes which we calculated are within 1° of those given by the original publications. Our expected paleolatitudes calculated for the Cretaceous units are slightly different from those given in most of the publications. This difference is due to our use of the recently revised Cretaceous reference pole of Globerman and Irving [1988]. For the

Jurassic the choice of paleomagnetic reference poles is less straightforward and is a critical part of our analysis. A detailed discussion of this topic is given in the main text.

The apparent northward transport is given by the difference between the expected and observed paleolatitudes:

$$\mathrm{DISP} = \lambda_x - \lambda_o \qquad (6)$$

where DISP is northward transport, λ_x is expected paleolatitude, and λ_o is observed paleolatitude.

The 95% confidence limits on apparent northward transport are estimated by

$$\Delta\mathrm{DISP} = 0.8\sqrt{A_r{}^2 + (d\lambda)^2} \qquad (7)$$

where A_r is the 95% confidence limit on the paleomagnetic reference pole, and $d\lambda$ is the 95% confidence limit on the observed paleolatitude given by equation (3).

The factor of 0.8 comes from the analysis of Demarest [1983]. Although not explicit in the paleolatitude comparison employed here, comparison of observed and expected paleolatitudes amounts to comparison between observed and reference paleomagnetic poles. The 0.8 factor is explicitly applicable to confidence limits on comparison of poles and implicitly applicable to confidence limits on paleolatitude comparisons. The resulting confidence limits are likely minimum estimates of uncertainties for studies involving small numbers of paleomagnetic sites with attendant uncertainties about sampling of geomagnetic secular variation.

The vertical axis rotation R is defined as positive for an observed direction clockwise from the expected direction and is given by

$$R = D_o - D_x \qquad (8)$$

where D_o is the observed declination, and D_x is the expected declination determined from the reference pole.

The confidence limit on vertical axis rotation, ΔR, is given by

$$\Delta R = 0.8\sqrt{\Delta D_o^2 + \Delta D_x^2} \qquad (9)$$

where

$$\Delta D_x = \sin^{-1}\left(\frac{\sin A_r}{\sin p}\right) \qquad (10)$$

$$\Delta D_o = \sin^{-1}\left(\frac{\sin \alpha_o}{\cos I_o}\right) \qquad (11)$$

and p is the great circle distance from the reference pole to the site.

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